Remote Sensing of Convective Clouds with Microwave Limb Sounder

Dong L Wu
M/S 183-701, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. Email: dwu@mls.jpl.nasa.gov

Abstract

Deep convection lifts up many large ice particles to upper troposphere where they can be detected with microwave sensors from space. Using limb-viewing technique, Microwave Limb Sounder (MLS) has unique advantages to measure these high clouds and their ice mass with good vertical resolution. Unlike IR/Visible techniques, microwave sensors can penetrate through dense-and-thick clouds to sense cloud ice mass. At high tangent heights, scattering from large ice particles produces radiances that are warmer than allowed for clear sky background. The difference, hence, is what we call the cloud radiance. Our model simulations show that the amount of ice in the instrument's field-of-view is proportional to the cloud limb radiance. This paper demonstrates an ice water content (IWC) retrieval (six levels in 200-50 hPa) based on the cloud radiances at high tangent heights. We use at with UARS (Upper Atmosphere Research Satellite) MLS 203 GHz measurements. The retrieval is divided into three steps. First, we determine the so-called cloud radiances (dT_b) for each lim radiance measurement, and compute seasonal average maps at 58, 76, 100, 131, 171, and 225 hPa (separated by ~2 km). Second, we convert these cloud radiances to limb ice water path (IWP) using model calculated dT_b-IWP relation. Third, we apply a simple or Abel inversion to retrieve IWC from the calculated IWPs at these pressure levels.

1. Cloud Signatures in UARS MLS Radiances

The UARS (Upper Atmosphere Research Satellite) MLS, launched in September 1991, has three radiometers (63, 205, 183 GHz) and six 15-channel filter bank spectrometers to measure temperature, O_3, ClO, and H_2O profiles in the stratosphere and lower mesosphere. Although it was designed for cloud observations, the channels around 203.5 GHz can detect many dense-and-thick clouds in the upper troposphere through radiances from ice scattering. In the normal operation, MLS step-scans the atmospheric limb from 90 km to the surface in ~65 seconds and each radiance measurement has a 2-second integration time. In the upper troposphere, the limb radiance measurements are separated by ~3 km in tangent height and by ~15 km in the horizontal direction because of satellite movement (~7.5 km/s). The instument views 90° from the spacecraft traveling direction, which gives a latitudinal coverage of 34° in one hemisphere to 80° in the other because of the 57° orbital inclination. The satellite is commanded to perform 10 maneuvers a year, which allows alternating views of high latitudes in the two hemispheres.

Clouds can either increase or decrease limb radiances depending on the tangent height viewed. As shown in Figure 1 (MLS 203-GHz radiances vs. tangent pressure), clear-sky radiances are mostly bounded by two lines and cloud radiances are mostly out-fliers. Clear-sky radiances increases with decreasing tangent heights at this frequency mainly because of the emissions from dry-air and water vapor continua. At high tangent heights, where clear sky backgrounds are low, cloud radiances can be readily seen as unusual enhancements due to ice particle scattering or emission. At low tangent heights, where clear-sky radiances are often saturated, cloud radiances manifest themselves as brightness temperature depressions because of scattering due to large ice particles. These are the two tangent height ranges where clouds can be observed in microwave limb radiances with good confidence. There is always an ambiguous tangent height region in the limb radiances where cloud effects are blended with water vapor variability and become difficult to detect.

In this study, we use only cloud radiances at high tangent heights for the cloud ice retrieve. Thus, the measurements reflect mostly the high clouds associated with deep convection.

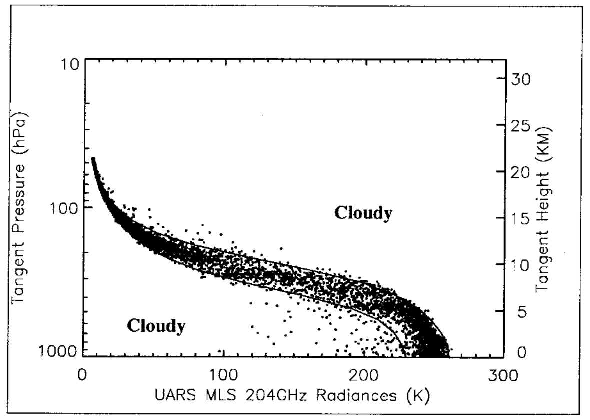


Figure 1

2. Undersampling Issue

Figure 2 shows a distribution of cloud radiances at ~13 km tangent height, which has a high degree of variability among different scans and even among different tangent heights. Because convective clouds are largely varying in space and time, the MLS sampling described above can hardly resolve each cloud structure. To use MLS cloud radiances properly, we must average them at each height-latitude-longitude grid so that the small-and meso-scale inhomogeneity is mostly washed out. Thus, for these monthly/seasonal averages we may assume homogeneity within each grids and retrieve cloud ice profiles from the cloud radiances at different tangent heights.

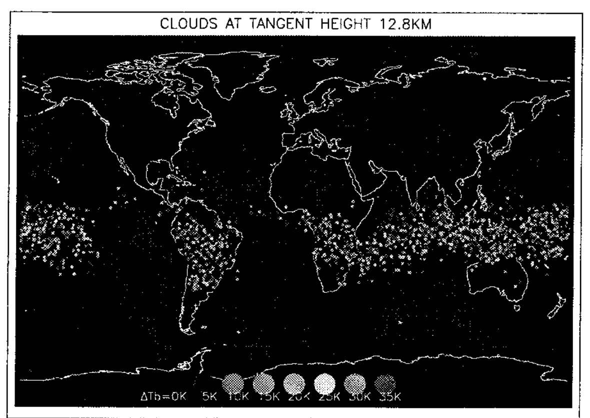
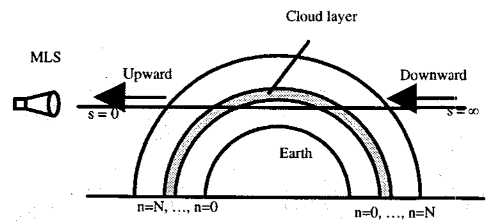


Figure 2

Figure 3



3. Radiative Transfer Model

To study the cloud radiances in limb-viewing cases, we develop a radiative transfer model that incorporates both gas emissions and hydrometer scattering along the line of sight (LOS). Unlike the plane-parallel models, the geometry to compute top-of-atmosphere (TOA) radiances in this model is illustrated in Figure 3 where the atmosphere is divided into a set of spherical shells. The TOA radiance (I) is observed at the $s=0$ shell of the LOS. At present, the model ignores polarization differences of the radiances, and the radiative transfer equation is given by

$$\frac{dI}{ds} = -k_e I + k_a B + k_s J \tag{1}$$

where gas and cloud coefficients are defined as follows:

$k_e = k_{gas\_a} + k_{c\_s} + k_{c\_a}$	*total extinction coefficient,*
k_{gas_a}	*gas absorption coefficient,*
k_{c_s}	*cloud scattering coefficient,*
k_{c_a}	*cloud absorption coefficient;*
$k_a = k_{gas\_a} + k_{c\_a}$	*total absorption coefficient;*
$k_s = k_{c\_s}$	*total scattering coefficient.*

The source function B is the Planck function of the air in temperature T. J represents the augmentation from cloud ice/liquid scattering contributions in all directions,

$$J = \frac{1}{4\pi}\oint P(\Omega,\Omega')I(\Omega')d\Omega' \tag{2}$$

where Ω is the solid angle of the radiation at LOS, Ω' is one of scattered lights around the cloud. The difference between Ω and Ω' is the scattering angle used in phase function P.

For clear-sky atmosphere, the model uses the line-by-line method to compute the absorption coefficients from major gas molecules at 1-1000 GHz: O_2(44 lines), H_2O (31 lines), $O^{18}O$ (93 lines), and O_3 (722 lines). The contribution from dry air continuum is the same as used in Liebe [1989]. The water vapor continuum is calculated using the function that Godon et al. [1992] obtained from laboratory measurements at 213 GHz. The magnitudes are adjusted slightly so as to fit better the measurements at 239 GHz [Bauer et al., 1995], 190 GHz [Bauer and Godon, 1991], 153 GHz [Bauer et al., 1993], and the ratio of UARS MLS 186.5/203.2 GHz absorption coefficients. In the current configuration surface temperature and reflectivity are simply equal to constants, 288 K and 0.8, respectively.

We assume all cloud hydrometers are made of spherical particles. For ice clouds we approximate ice crystals with *equivalent spheres.* Therefore, the parameterization used to characterize the size distribution is based on the mass-equivalent spheres, with diameter $D = (6M/\pi\rho_{ice})^{1/3}$ where M is the mass of ice particles and $\rho_{ice} \approx 0.91$ g/cm^3 is ice density. Mie theory is applied to obtain scattering/extinction coefficients at each particle size and we integrate the coefficients over all sizes using the particle size distribution developed by McFarquhar and Heymsfield [1997, or MH97]. The MH97 distribution can reproduce many bimodal distributions seen in dense-and-thick clouds, which is very important for interpreting 100-600 GHz radiances. The complex refractive index of ice, m_i, is computed using the empirical model developed in Hufford [1991]. A 64-stream integration is used in the scattering calculations, and each limb radiance is computed along the LOS from the very far side of the ray down to the tangent point and back up to the instrument. In doing so, Eq.(1) is solved with the iterative approach such that the convergence in all limb radiances is found.

4. Sensitivity to Ice Cloud Parameters

We further study the sensitivities of limb radiances to cloud optical depth (τ) and ice water path (IWP) using the radiative transfer model described above. Here, we define the sensitivities as the cloud radiances ΔT_b (cloudy-clear radiances) with respect to these cloud variables. Because of the limb-viewing geometry, the cloud τ and IWP should be considered as the quantities along the LOS, which are different from the nadir cases. In optically-thin situations (or at high tangent heights) they can be related to cloud volume extinction coefficient k_e and ice water content (IWC) in a simple form as follows:

$$\tau(z_t) = 2\int_{z_t}^{\infty} k_e(z)ds = \int_{z_t}^{\infty} k_e(z)\frac{2zdz}{\sqrt{z^2 - z_t^2}} \tag{3}$$

$$IWP(z_t) = 2\int_{z_t}^{\infty} IWC(z)ds = \int_{z_t}^{\infty} IWC(z)\frac{2zdz}{\sqrt{z^2 - z_t^2}} \tag{4}$$

Figures 4-5 show the sensitivities of limb cloud radiances (204 GHz) to τ and IWP for various tangent heights where a 1-km cloud layer is placed at 16km. The relations are fairly linear for small τ and IWP at most tangent heights but become saturated as $\tau > 1$ or IWP > ~10 kg/m^2. The saturation occurs because the cloud becomes opaque and the radiation cannot penetrate deep into the cloud. These correspond to some very extreme cases and rarely happen in reality as we will see in MLS observations. The sensitivities diminish at low tangent heights as the clear-sky background and the variability due to water vapor increase rapidly. Hence, the optically-thin condition fails at low tangent heights and so does this cloud observation technique. Generally speaking, the limb radiances below 13 km tangent height cannot be used with this method. To retrieve these cloud parameters, the ΔT_b- τ and ΔT_b-IWP relations can be further fit to an analytical form as expressed in Figures 4-5 for the unsaturated portion. These functions can be used to determine the cloud τ and IWP at each tangent height once a ΔT_b is given.

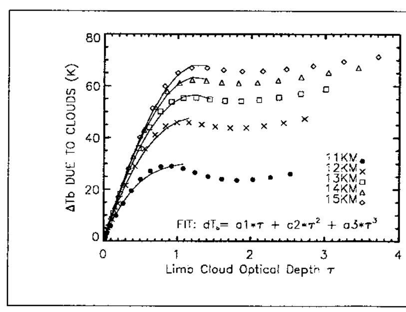


Figure 4

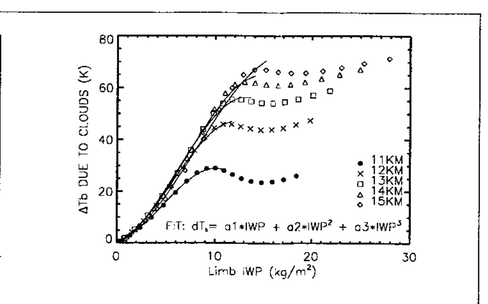


Figure 5

5. Cloud Ice Retrieval

To illustrate this cloud ice retrieval, we use UARS MLS 204 GHz measurements during the period of December 1992 - February 1993. The data are averaged into 5°x10° latitude-longitude grids for every ~2 km tangent height. Since the MLS measurements are registered to tangent pressure, we report cloud maps at a constant pressure. There are three key steps in the retrieval: (1) obtaining cloud radiances (ΔT_b) [Figure 6], (2) converting ΔT_b to limb IWP for each tangent pressure [Figure 7], and (3) retrieving IWC from the IWP determined in step 2 [Figure 8].

Figure 6 Cloud Radiances (ΔT_b)

At high tangent heights, cloud radiances are determined as the difference above the maximum clear-sky value (where 110% saturation is assumed). Such calculation is performed within each scan since the air temperature may vary largely from place to place. The minimum cloud detection threshold is 3 K, which accounts for uncertainties in the clear-sky radiance calculation. Hence, many thin-and-light clouds will not be detected, making the MLS observations biased primarily to the clouds from strong deep convection. As seen in the maps on the right, where a 1-2-1 smooth is applied, there are a significant number of clouds reaching up to ~60 hPa (or ~21km) in the tropics, over South Africa, South America, and the west Pacific Warm Zone. Another interesting feature is the large amount of high clouds (between 130-60hPa) at northern high latitudes, which is still being investigated and could be related to the wintertime cirrus often seen by ground-based lidars.

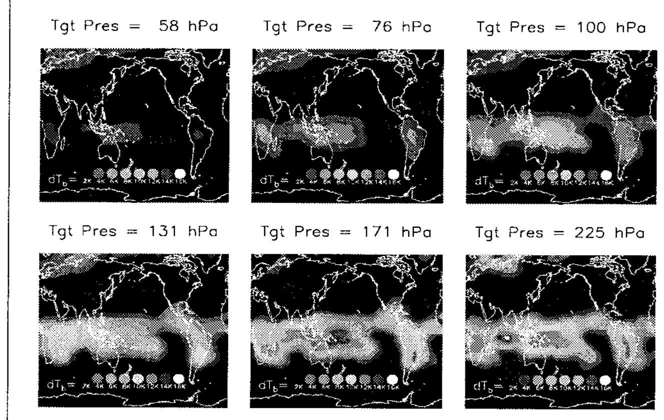


Figure 7 Limb Ice Water Path (IWP)

The limb cloud radiances are proportional to ice mass inside the instrument's field of view (FOV) in the way described in Figure 5. At each tangent pressure, we may convert the cloud radiances to IWP using the curves fitted there. Since all cloud radiances occur in the linear range of the ΔT_b-IWP relation, the IWP maps essentially preserve the patterns seen in the ΔT_b maps. The estimated error for IWP is 1.3 kg/m^2, which is directly based on the cloud radiance error and excludes any error from the modeled ΔT_b-IWP relation.

In this step, we may also convert the cloud radiances to limb cloud optical depth using the ΔT_b- τ relation found in the previous section. It is noted that the ΔT_b- τ relation is hardly affected by the size distribution used, and therefore the optical depth retrieval has a great advantage by eliminating any assumption about size distribution and the uncertainties associated. The limb optical depth can be further used to retrieve cloud extinction profiles by assuming layer homogeneity over the distance of LOS.

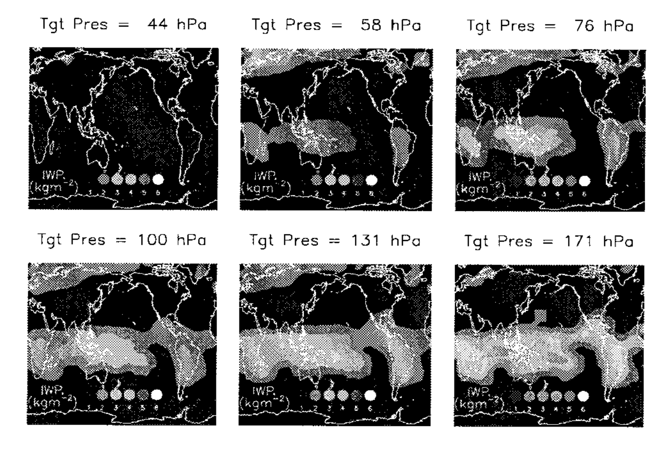
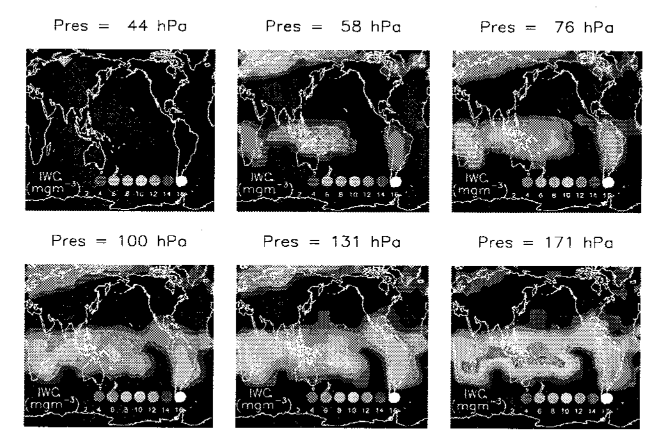


Figure 8 Ice Water Content (IWC)

The limb IWPs are related to IWC through Eq.(4) where the weighting functions are known as Abel kernel that is very sharp at the tangent point. The sharp weighting functions allow us to resolve IWC profiles with good vertical resolution. For this reason, MLS can provide more reliable and quantitative information about ice mass in the upper troposphere and lower stratosphere than nadir-viewing techniques. Furthermore, the MLS IWC observations can help constrain the cloud ice calculations from numerical weather/climate models and improve the convection and cloud parameterizations used in the models.

For the IWC inversion, we simply use the onion-peeling technique since IWC vanishes at the top of atmosphere but increases with pressure in the upper troposphere. The IWC error, which is passed along from IWP, is estimated to be ~4 mg/m^3 for the 2km vertical resolution.



6. Conclusions

- Microwave limb radiances interact almost linearly with cloud ice in the instrument's field of view. Such property allows a reliable retrieval of ice mass profile, with good vertical resolution, in convective clouds in the upper troposphere.
- UARS MLS 204GHz observations suggest that many convective clouds in the tropics can reach as high as ~60 hPa over strong deep convection zones such as South Africa, South America, and the western Pacific during December-February.
- For a 2km resolution, the IWP and IWC retrievals on the seasonal mean maps have accuracy of 1.3 kg/m^2 and 4 mg/m^3, respectively.
- Because of good vertical resolution in the upper troposphere, MLS IWC measurements at 170-44 hPa can be used to validate results from numerical weather/climate models and help reduce uncertainties that are associated with convection/cloud parameterizations. It is also possible to directly compare modeled cloud extinction coefficients to MLS observations at these altitudes since they are least affected by the size distributions used.

7. Future Work

- Cloud ice can be also retrieved using radiances at low tangent heights where brightness temperature depressions are found. These radiances are sensitive to both high-level convective clouds and mid-level frontal clouds. Large ice particles in these clouds can cause brightness temperature depressions as high as 150K at low tangent heights. The retrieval using the depressed radiances should be able to extend cloud ice profiles down to ~5 km.
- A new MLS instrument, known as EOS MLS, will be flown on NASA EOS Aura (previously known as EOS-CHEM satellite) in 2004 and will house five radiometers at 118, 190, 240, 640 GHz and 2.5 THz. The more frequency selections will be available to allow both ice mass and particle size information.